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SANDIA HIGH PRESSURE ABLATION TEST IN THE AEDC 5-MEGAWATT ARC HEATER TEST UNIT SERIES II

J. R. Henson

ARO, Inc.

January 1968

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NOTICES

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J. R. Henson
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FOREWORD

The test reported herein was sponsored by the Sandia Corporation under Atomic Energy Commission (AEC) Contract No. AT(29-1)-789. The Program Area is 921Z.

The results of the test were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The work was accomplished in the 5-Megawatt Arc Heater Test Unit of the Propulsion Wind Tunnel Facility, under ARO Project No. PL1824, from October 9 to 13, 1967. The manuscript was submitted for publication on December 15, 1967.

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This technical report has been reviewed and is approved.

Richard W. Bradley	Leonard T. Glaser
Lt Colonel, USAF	Colonel, USAF
AF Representative, PWT	Director of Test
Directorate of Test	

ABSTRACT

Three ablation test runs, involving 15 test models, were made in an arc-heated free-jet facility using air as the test fluid. Test runs were conducted to screen and examine the ablation performance of various materials with different microscopic structure. The investigation was accomplished at Mach number 2.3 with measured reservoir pressures ranging from 98 to 100 atm and enthalpies from 2310 to 2530 Btu/lb. Test models were hemisphere-cylinder specimens of composite materials. Most of the models were instrumented with a thermocouple embedded inside the specimen. The data measured during the present investigation are presented in a documentary manner with a minimum of analysis because the composition of the model material is proprietary. The models are referred to by number designation only.

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NOMENCLATURE

D	Diameter, in.
C_D	Venturi discharge coefficient
h_t	Total enthalpy, Btu/lb
I	Arc heater current, amp
$\dot{m}$	Mass flow, lb/sec
P_A	Power to arc heater, kw
P_B	Anode and cathode losses, kw
P_D	Nozzle losses, kw
p_t	Arc heater reservoir pressure, atm
V	Arc heater voltage, v
ΔL	Change in model length by ablation, in.
Δm	Change in model mass by ablation, gm
ΔT	Cooling water temperature rise, °F
Δt_m	Model exposure time, sec
η	Arc heater efficiency

SUPERSCRIPT

*	Throat condition

SECTION I
INTRODUCTION

The primary objectives of the Sandia ablation program are to examine the ablation performance of materials with different microscopic structure and to determine the change in microscopic structure that occurs during ablation under high pressure and temperature. The accomplishment of these objectives is being supported by ablation testing in the 5-Megawatt Arc Heater Test Unit of the Propulsion Wind Tunnel Facility (PWT) located at the Arnold Engineering Development Center.

The physical composition of the models investigated and reported on herein is proprietary to the Sandia Corporation. A further description of the model composition is available from the Sandia Corporation.

This report presents the documented test results, a description of the test facility, model configuration, instrumentation, and operational procedure for the test program.

SECTION II
APPARATUS

2.1 5-MEGAWATT ARC HEATER TEST UNIT

The 5-Megawatt Arc Heater Test Unit[1] is a continuous flow, arc-heated facility using air and is being used to conduct ablation studies of materials over a wide range of re-entry conditions. An electrical line diagram with the power supply, ballast, and arc heater is shown in Fig. 1 (Appendix I). The test unit configuration used for the Sandia test program consisted of the arc heater, test nozzle, model injection system, and the exhaust ducting (Fig. 2).

A sectional view of the arc heater is shown in Fig. 3. The rear electrode (silver-copper alloy) is the anode, and the front electrode (tough pitch copper) is the cathode. Demineralized water is used to cool the electrodes during heater operation. The coil surrounding the anode generates a magnetic field which interacts with the arc column, causing

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[1] Test Facilities Handbook (6th Edition). "Propulsion Wind Tunnel Facility, Vol. 5." Arnold Engineering Development Center, November 1966.

the arc termination in the anode to rotate rapidly, which minimizes melting of the anode material. Air flows into the arc heater through six tangentially oriented orifices, generating a vortex, which helps to rotate the cathode termination of the arc column and also provides a centrifuging effect to keep relatively cooler air at the cathode surface.

A supersonic water-cooled nozzle is used to provide a free-jet Mach number of 2.3 at the nozzle exit plane. The convergent section of the nozzle is conical and is joined to a circular arc section which extends to the throat. The nozzle expansion is contoured to produce uniform, parallel flow. All of the test runs are performed with the nozzle discharging to atmospheric pressure, and the value of reservoir pressure is such that the nozzle is operating underexpanded. Design details of the Mach 2.3 nozzle are shown in Fig. 4. Pertinent nozzle dimensions for the Sandia test program are given below. The change in throat and exit diameters can be attributed to deposit from the eroding of the anode and cathode.

Pretest					
Mach Number	Convergent Half-Angle		Radius of Curvature to Throat, in.	D*, in.	D_{exit}, in.
	Deg	Min			
2.3	42	50	0.875	0.375	0.617
Posttest					
2.3	---	---	0.875	0.372	0.615

A multiple-head, side-injection model support system injects from one to five models into the jet for preset dwell times from 0 to 15 sec. The support system is hydraulically actuated and remotely controlled. Arc chamber conditions remain constant for all models, and transit time is approximately 0.50 sec, from position to position. The injection of models transverse to the axis of the jet minimizes the transit time from the boundary to the center of the jet. A photograph of the injection system is shown in Fig. 5.

The exhaust system consists of a short section of water-jacketed ducting (36-in. OD), a section of uncooled ducting (36-in. OD), and a vertical duct (24-in. OD), with a single stage, axial-flow fan discharging to atmosphere.

2.2 TEST UNIT INSTRUMENTATION

Test unit instrumentation consists of visual indicators and recording equipment. Visual observation of pressures is accomplished by use of Autosyn® transmitters and indicators. Test unit temperatures are monitored by means of various kinds of thermocouples. Water flow rates are measured with turbine-type flowmeters and pulse rate converters. Arc voltage and current are measured by use of a voltage divider and a current shunt. A 36-channel recording oscillograph is used to record all data necessary to calculate arc heater performance. A closed-loop television system is used to view the models during each test run.

2.3 MODEL INSTRUMENTATION

Tungsten-tungsten 26-percent rhenium thermocouples (W/W-26-percent Re) were used to measure model internal temperatures. All thermocouples used were furnished and installed in the models by the Sandia Corporation. Brightness temperatures of the model ablating surfaces while in the flow and during cooldown were measured by means of pyrometers developed and fabricated by the Johns Hopkins University Applied Physics Laboratory[2]. The outputs from the pyrometers were recorded by oscillograph recorders.

Three motion-picture cameras were used for documentation of model ablation. These were 16-mm cameras, using color film and operating at speeds up to 600 frames/sec. Camera locations, lens settings, types of filters, film used, and operating speeds are presented in Table I (Appendix II).

Data from the recording oscillograph and the cameras were correlated from timing marks generated by a transistorized timing signal device.

2.4 DESCRIPTION OF MODELS

All models were furnished by the Sandia Corporation. The ablation sample configuration was a hemisphere-cylinder. The hemisphere nose radius was 0.2 in.; the cylinder diameter was 0.40 in. A typical pretest

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[2]Hill, M. L., Aldridge, J. M., and Keller, C. A. "Miniature Recording Optical Pyrometer." The Johns Hopkins University Applied Physics Laboratory, Report TG-825, May 1966.

photograph of an ablation sample is shown in Fig. 6. The ablation samples were constructed to accommodate one imbedded thermocouple. A sketch of the model assembly is shown in Fig. 7. Detailed information for the imbedded W/W-26-percent Re thermocouple is presented in Fig. 8.

The sample holder was fabricated from phenolic Refrasil® molded in a truncated cone-cylinder configuration. The cylinder diameter was 2.5 in. Components of a typical ablation model are shown in Fig. 9.

SECTION III
TEST PROCEDURE

3.1 MODEL PREPARATION

All test samples were photographed, weighed, measured, and assembled with holders before being installed for testing. A summary of model weights and measurements is presented in Table II. The thermocouples imbedded in the ablation samples were electrically checked before and after being mounted to the test unit injection system. Test models were positioned on the jet centerline with the tip of the hemisphere nose 0.05 in. from the nozzle exit plane.

After the test was completed, the models were photographed and shipped to the Sandia Corporation to be disassembled, weighed, and measured. Posttest model weights and lengths are also presented in Table II. These measurements were made by the Sandia Corporation.

3.2 TYPICAL TEST RUN

Prerun electrical calibrations were made of the arc heater unit and model instrumentation. Airflow to the heater, cooling water flow, and current flow to the arc heater magnetic coil were initiated; then the heater recording equipment was started, and the arc was energized by applying open-circuit voltage and moving the carbon-tipped starting rod close to the face of the anode seal shield (Fig. 3). The power level (using the tap-changing-under-load transformer) and airflow were increased to the required values, and approximately 20 sec was allowed for the cooling water discharge temperature to stabilize. After the heater conditions were stabilized, the model data recording equipment and motion-picture cameras were started. The models were then injected, with exposure time preset. After all models had been injected, the heater power was shut off, and a postrun electrical calibration of the instrumentation was conducted.

SECTION IV
TEST RESULTS

4.1 TEST RUN SUMMARY

Three test runs, involving five models per run, were made during the period covered by this report. A model test log is presented in Table III, in which pertinent model description, instrumentation, and dwell time information recorded on the 36-channel oscillograph is given. All test runs were accomplished using a Mach number 2.3 nozzle. The nozzle was operated underexpanded for all tests. The test unit was operated at reservoir pressures ranging from 98 to 100 atm and enthalpies from 2310 to 2530 Btu/lb. Closeup photographs of models were made after being exposed to the arc heater flow and are shown in Fig. 10.

4.2 HEATER TEST CONDITIONS

A summary of the arc heater operating conditions for the Sandia test is presented in Table IV. Target conditions for test runs were reservoir pressure (p_t), 100 atm and total enthalpy (h_t), 2600 Btu/lb. The reservoir pressure was within ±2 percent of the target condition for all runs. The total enthalpy repeatability was within -11 percent of the target condition. In view of the fact that enthalpy is affected by such things as the variation in voltage on the primary side of the 30,000-kva transformer (Fig. 1), surface condition of the heater electrodes, purity of the supply air, and accuracy of mass flow measurement, -11-percent variation in enthalpy is acceptable repeatability.

The input voltage and current to the arc heater were measured using a voltage divider and a current shunt. It is estimated that the uncertainty in determining the arc power input from these measurements is ±5.0 percent.

Air mass flow rates ($\dot{m}$) were measured by use of a choked venturi meter ($D^* = 0.1255$ in., $C_D = 1.0$), built to ASME standards. It is estimated that the uncertainty in measuring the mass flow is ±5.0 percent.

The total (reservoir) pressure (p_t) in the arc heater was measured by means of a wall pressure orifice in the heater swirl chamber located in the front shell seal. Some uncertainty is inherent in the pressure measurement because the velocity at the measuring station is not zero. The estimated uncertainty in measuring p_t is ±2.0 percent.

Total enthalpy (h_t) was calculated as follows:

$$h_t = \left[\frac{P_A - (P_B + P_D)}{\dot{m}} \times 0.948\right] + 100 \text{ Btu/lb} \tag{1}$$

The first term is the net enthalpy increment given the air by the arc heater and includes power losses to the arc heater and nozzle cooling water. The number 0.948 is to convert from electrical to thermal units. The second term in the equation is the enthalpy of the incoming air. Power to the arc (P_A) is obtained from arc voltage and current measurements. Power lost to the arc heater cooling water (P_B) is the sum of the anode and cathode losses, and P_D is the nozzle loss. Cooling water ΔT's were measured by thermistors with opposed emf's and whose bridge circuits incorporate passive shaping elements designed to make the thermistor outputs linear over the ΔT range from 0 to 40°F. A ΔT value derived from a differential thermocouple (copper-constantan) was used when the cooling water ΔT exceeded 40°F. Calibration of this system over a ΔT range from 0 to 90°F has shown the output to be linear. Combining all the uncertainties in measurements, it is estimated that the calculated total enthalpy values given in Table IV may be in error by ±8.0 percent (95-percent confidence level).

4.3 SAMPLE LOSS RATE AND RECESSION RATE

The loss rate and recession rate for the ablation samples investigated are presented in Table V. The loss rate, $\Delta m/\Delta t_m$, is the change in sample mass during exposure time. The recession rate is the change in sample length during exposure time. These parameters and a visual inspection of postmodel photographs (Fig. 10) provide a good comparative index from which a relative ranking of materials can be made. The samples which exhibited superior performance were 5Q-10, 5Q-11, 5Q-21, IP-1A, and IP9. It should be noted that the ranking of materials by loss rate and recession rate does not rule out the other samples for future testing. The IPBN samples were of lower density, and the ablation properties seemed fair. A complete evaluation of the ablation materials should include such parameters as the thermal conductivity, density, structure, and strength comparisons. An extensive ablation study of each material is being made by the Sandia Corporation.

4.4 TEMPERATURE DATA

All of the test samples except one were instrumented with one W/W-26-percent Re thermocouple. The thermocouples recorded internal sample temperatures during and after model exposure to the heater flow, depending on the amount of sample ablation or failure. The surface

temperature was measured by pyrometers during exposure to heater flow and during cooldown when the model was in the next lock position after exposure to flow.

4.4.1 Thermocouple Data

Recorded thermocouple data are presented in plotted form in Fig. 11. The zero time shown in the plotted figure is a common reference time for all models, corresponding to the time at which each model is locked into position in the heater flow. A comparison of the data shows a marked difference in the heat conductivity of the materials investigated. Model IPBN No. 1, Run S-6 results show a slow temperature rise with time during and after the time the model was exposed to the heater flow. The maximum temperature recorded for the model was 1900°F, 3.2 sec after lockin. The data recorded for models BY-12 No. 3, 1.8B, 1.8D, CVD-4A, and CVD-4C indicate high heat conductive materials with model CVD-4C internal temperature reaching approximately 4150°F, 2.1 sec after lockin. Models CVD-4A and BY-12 No. 3 show a higher heat conductive rate; however, both models ablated back to the thermocouple while in flow. No data were recorded for model PYC-F1-175 because of model failure during injection.

4.4.2 Pyrometer Data

The brightness temperature of the sample ablating surface was recorded by pyrometer No. 27. The recorded peak temperatures while models were exposed to the heater flow are presented in Table VI. Pyrometer No. 27 was filtered and focused just forward of the ablating sample shoulder.

The brightness surface temperature during cooldown was recorded from pyrometer No. 28. Pyrometer No. 28 was focused on the sample stagnation point in the next lock position after being exposed to the heater flow. The filter was removed from this pyrometer for better accuracy at lower temperatures. Time-history plots of the cooldown for each model except BY-12 No. 3 and PYC-F1-175 are presented in Fig. 12. Models BY-12 No. 3 and PYC-F1-175 failed before reaching the cooldown lock position.

APPENDIXES

I. ILLUSTRATIONS

II. TABLES

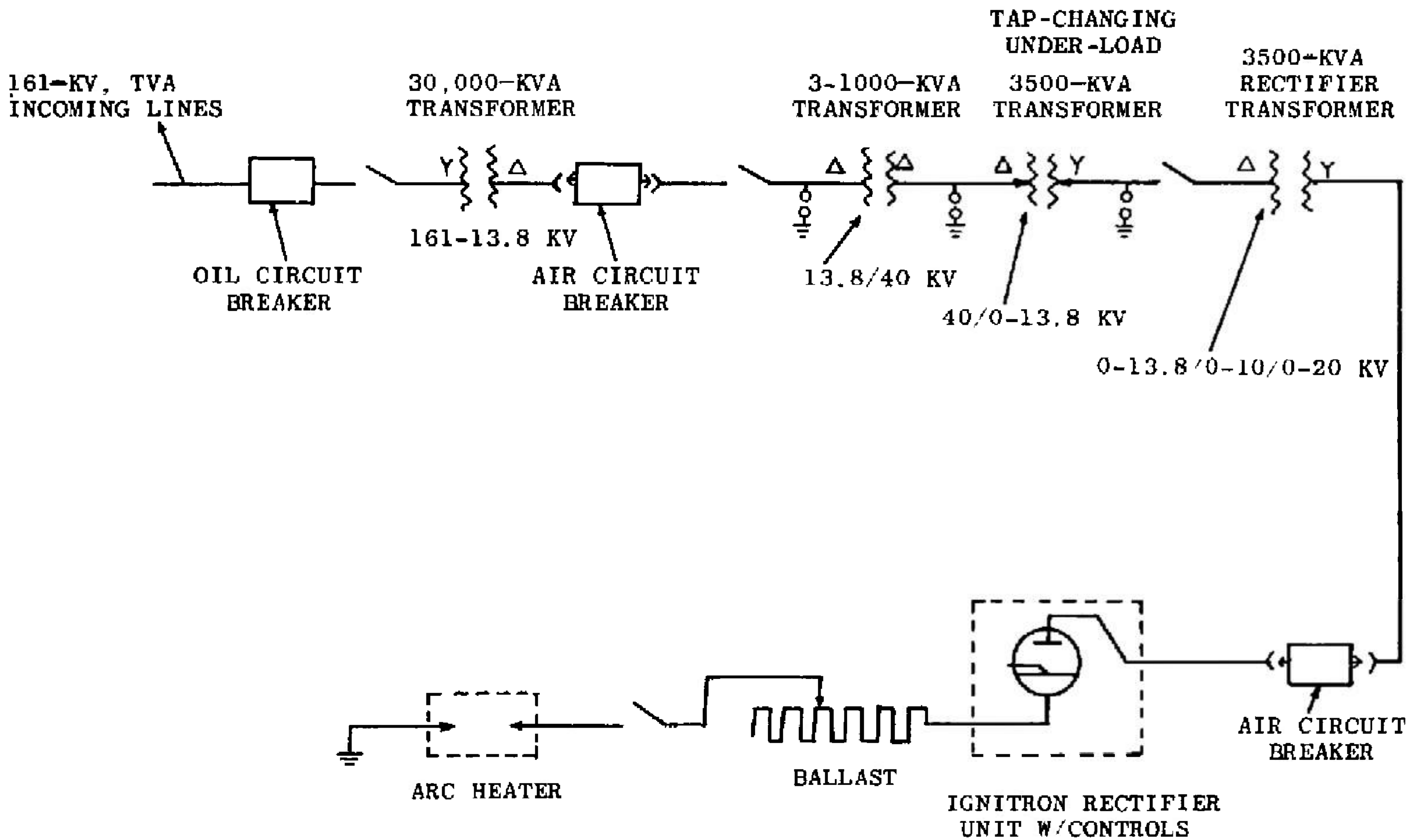


Fig. 1 Main Power Supply Line Diagram

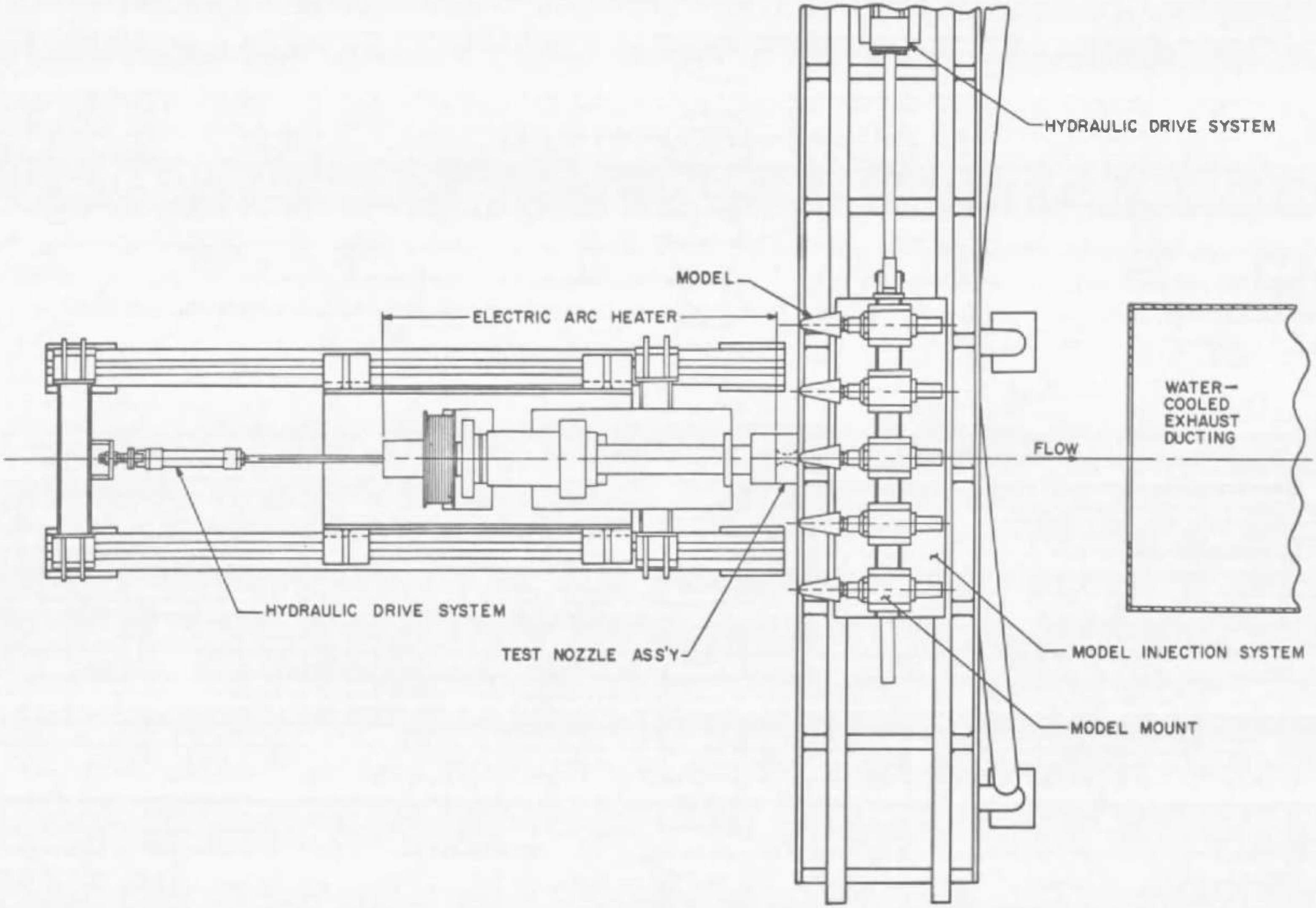


Fig. 2 5-Megawatt Arc Heater Test Unit

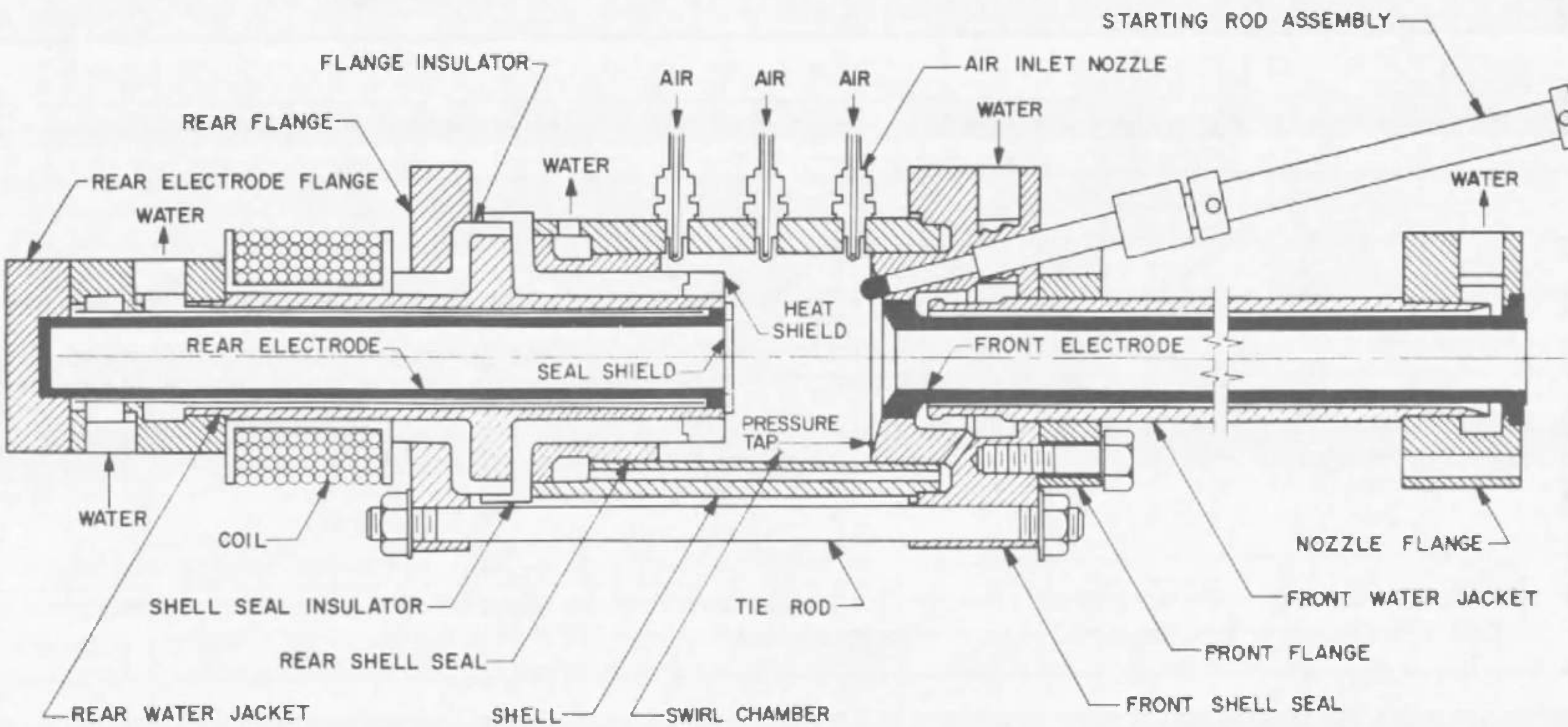


Fig. 3 Schematic of Modified Linde N-4000 Arc Heater

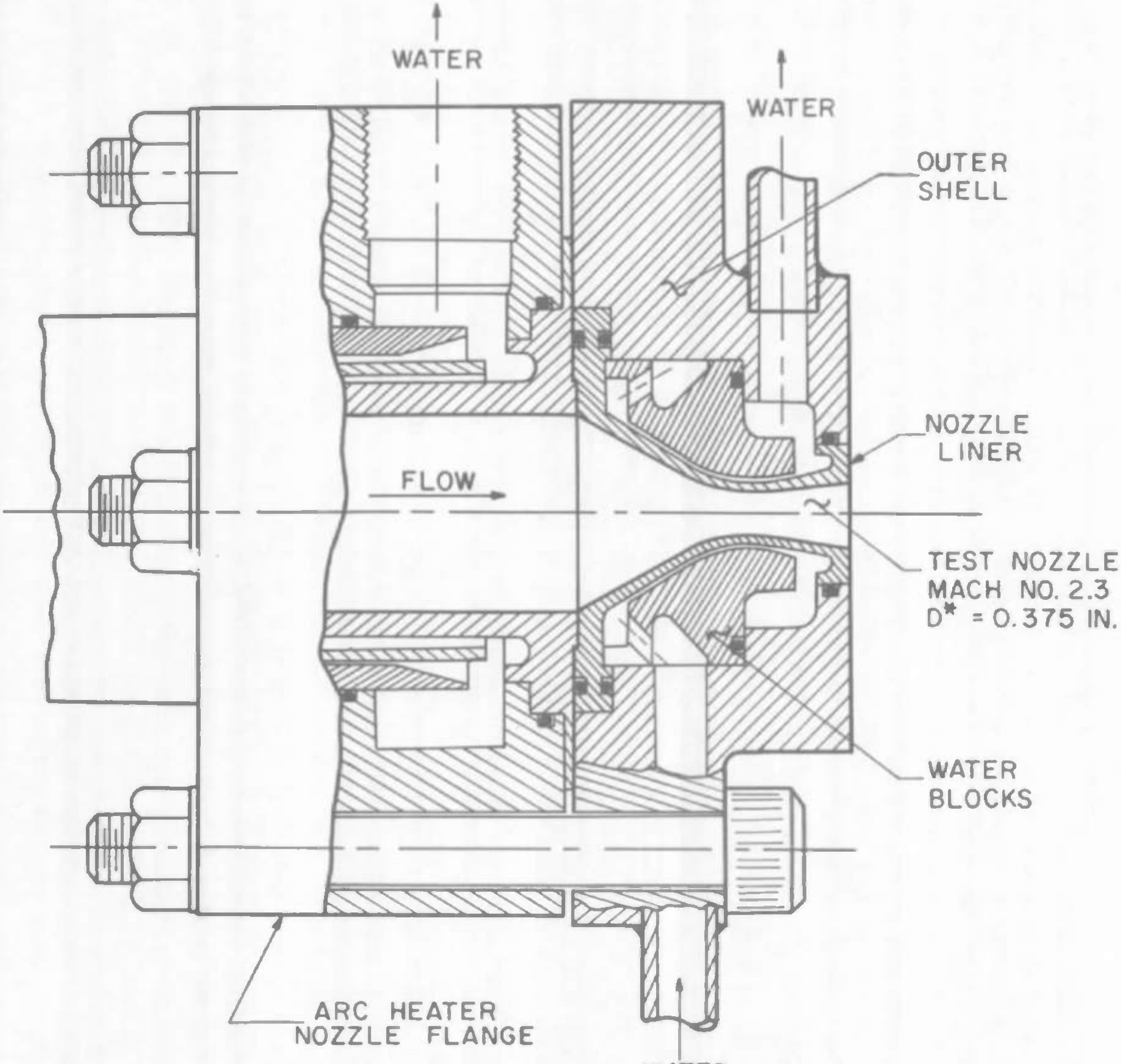


Fig. 4 Nozzle Configuration

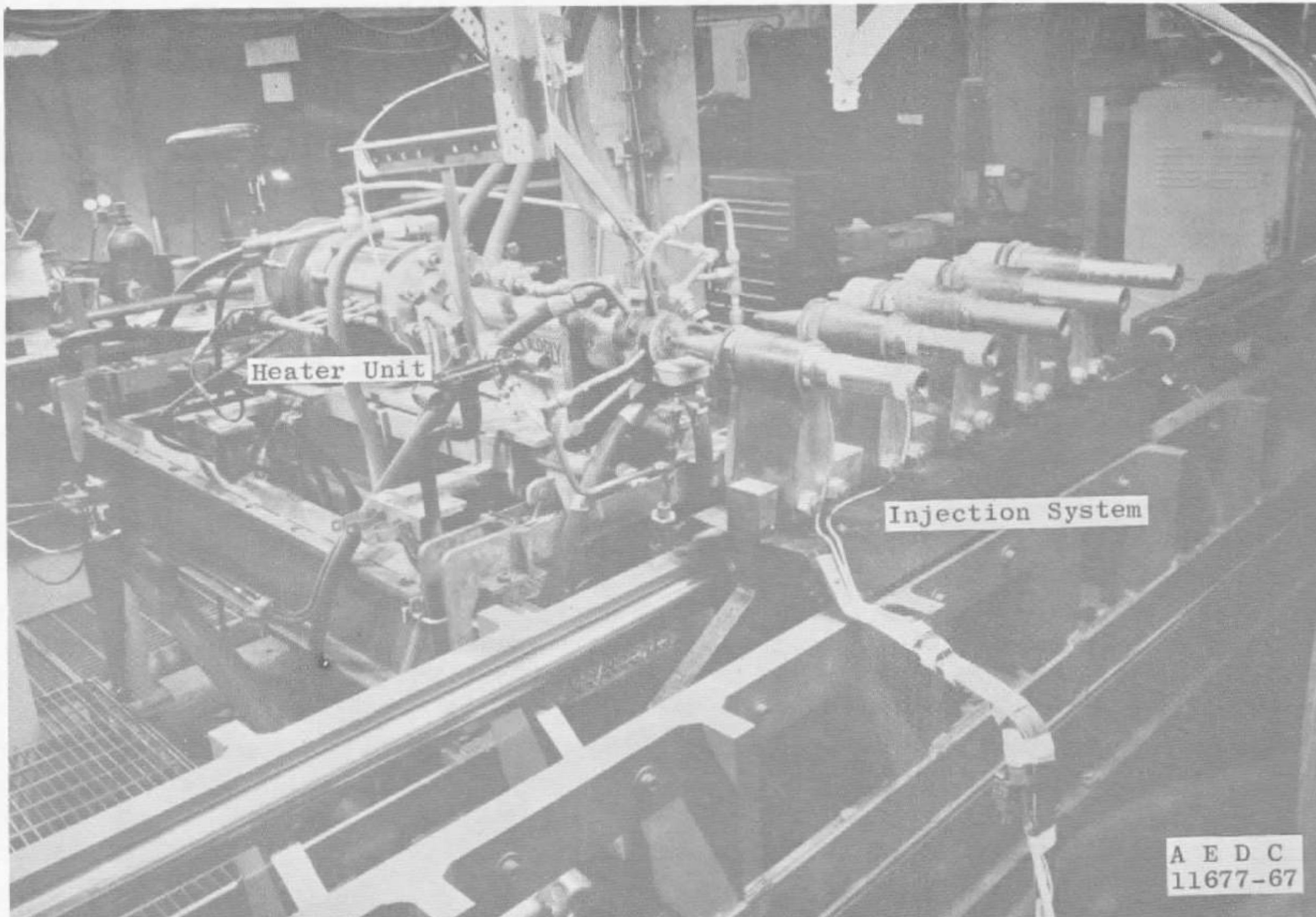


Fig. 5 Multiple Head Injection System

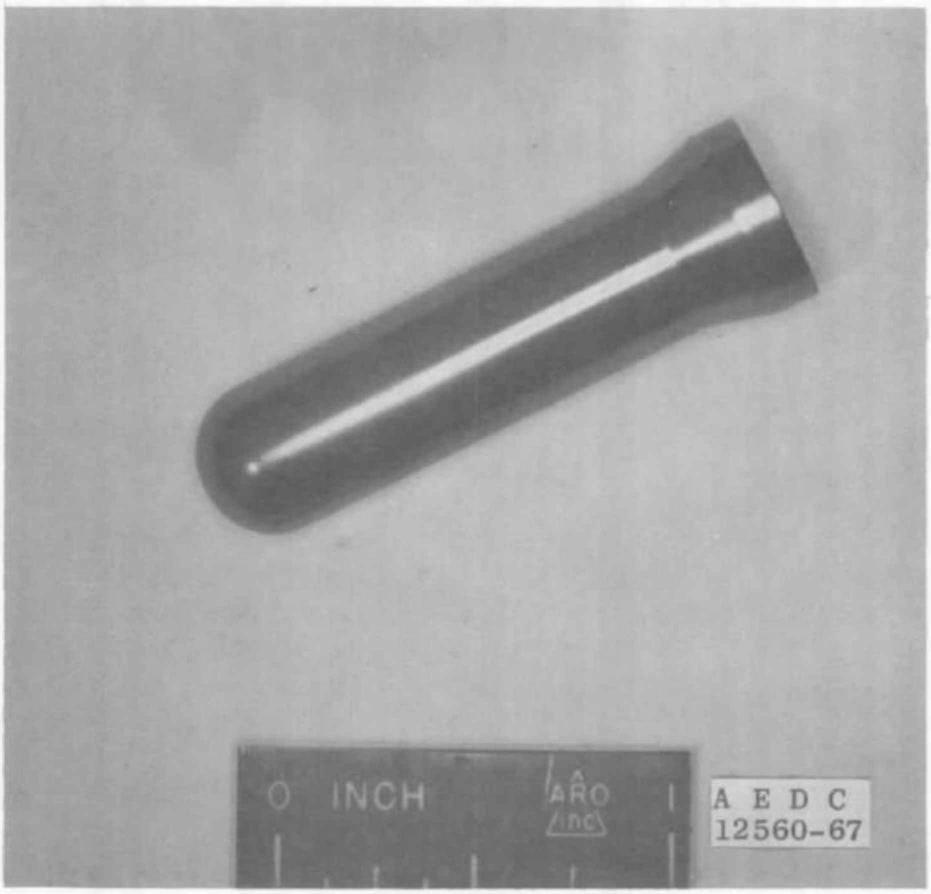


Fig. 6 Pretest Ablation Sample Photograph

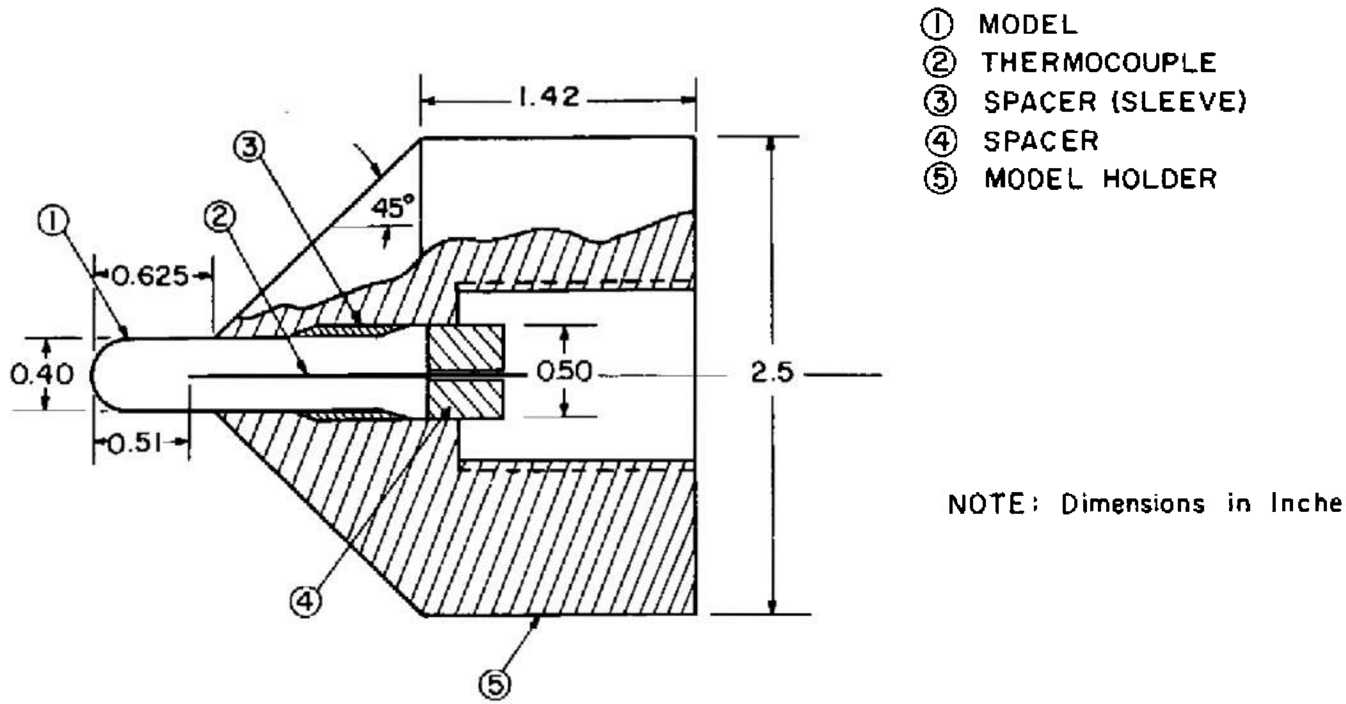


Fig. 7 Schematic of Ablation Model Assembly

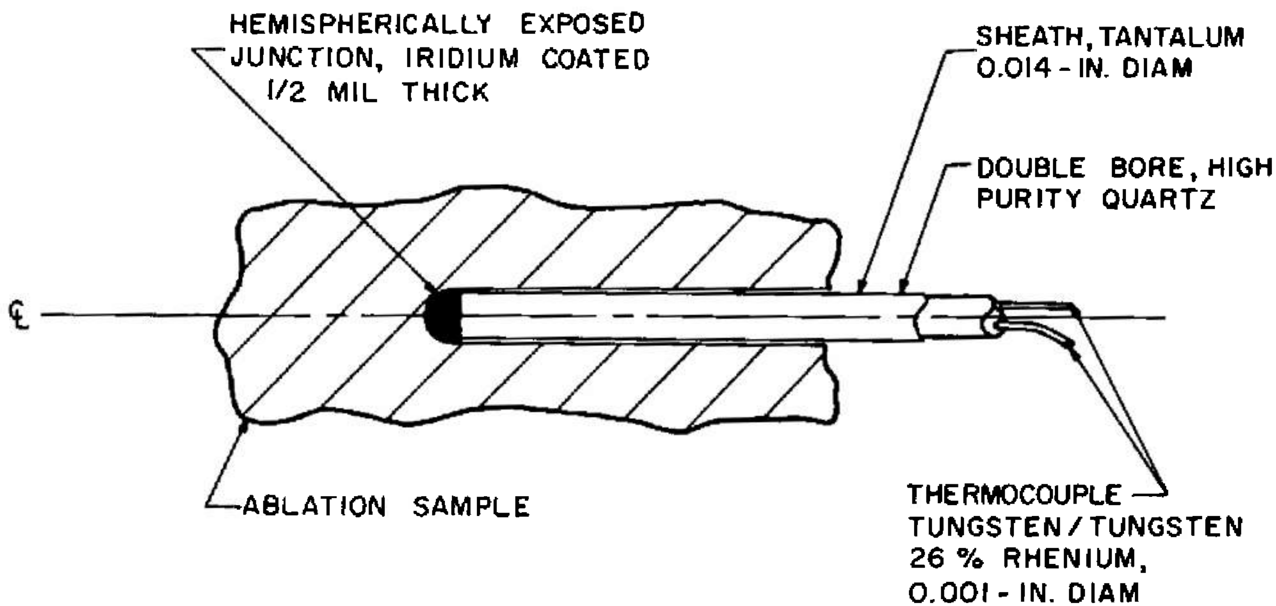


Fig. 8 Schematic of W/W-26-percent Re Thermocouple

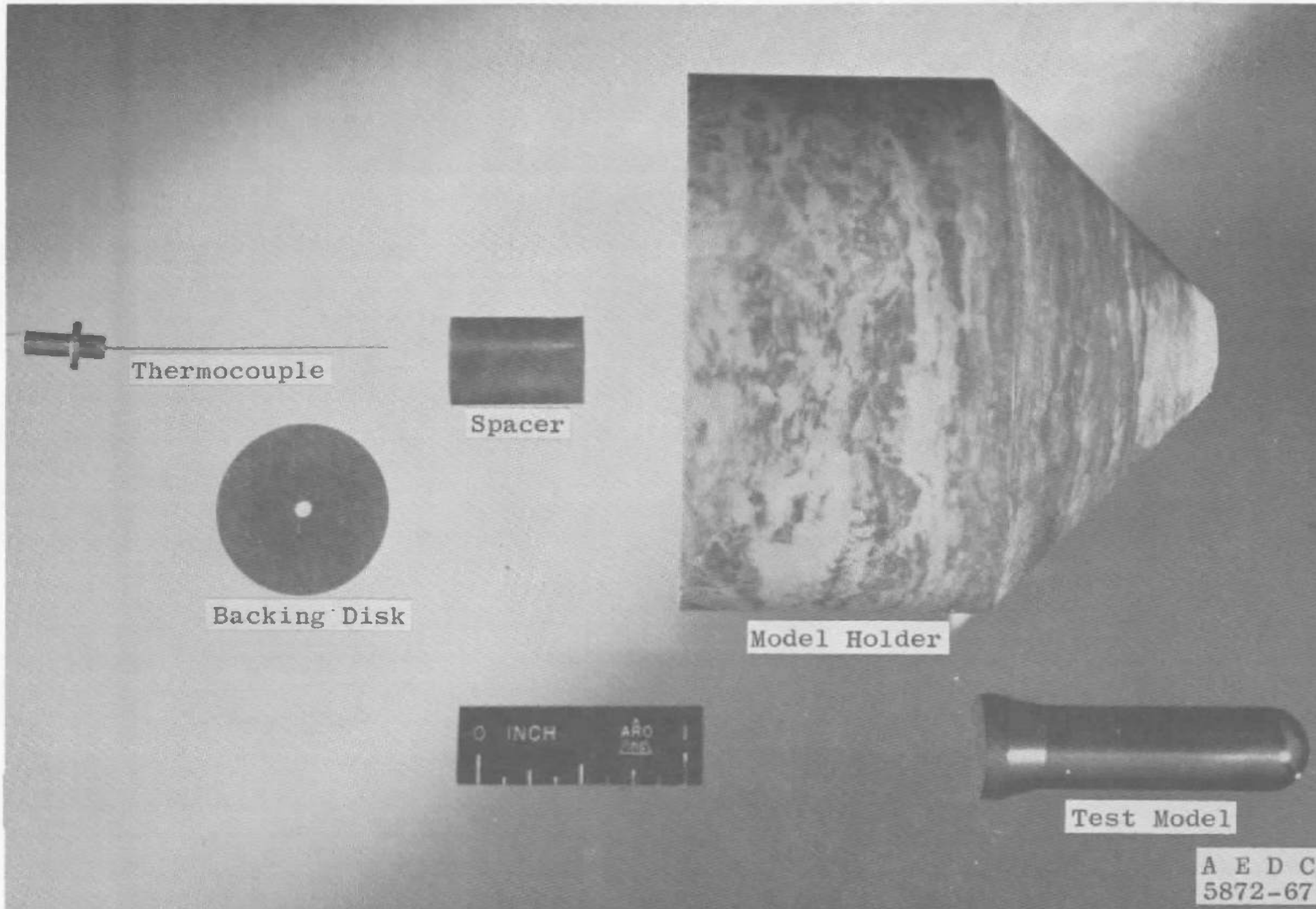
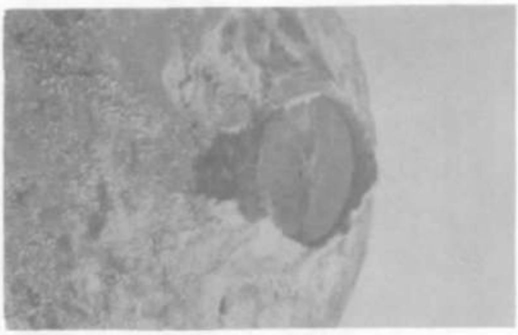
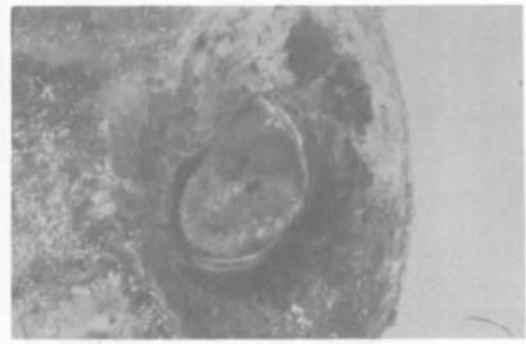


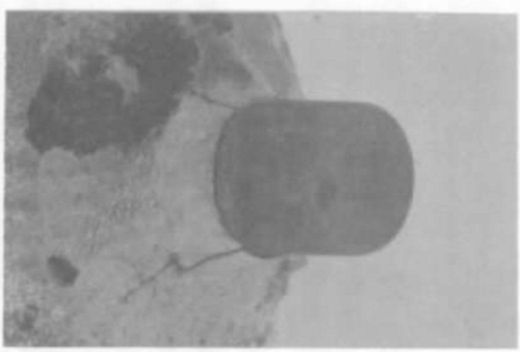
Fig. 9 Ablation Model Components



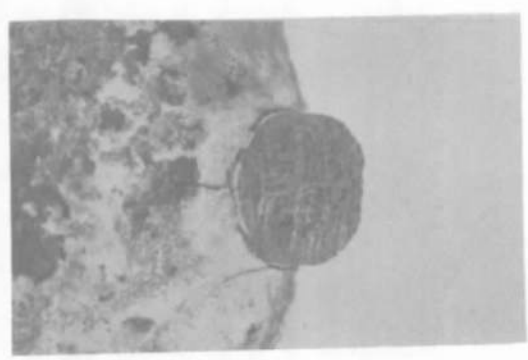
a. Model BY-12 No. 3



b. Model PYC-F1-175



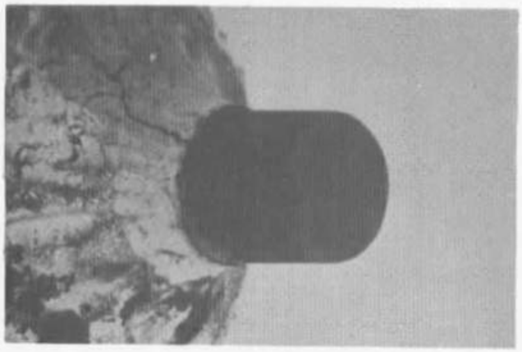
c. Model 5Q-10



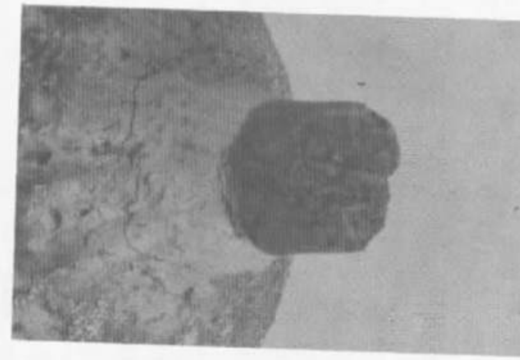
d. Model 1.8B

e. Model 1.8D

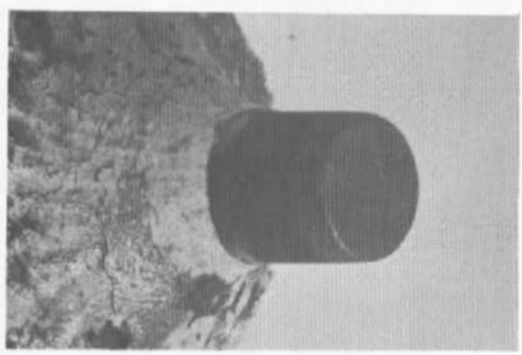
Fig. 10 Posttest Photographs of Ablation Models



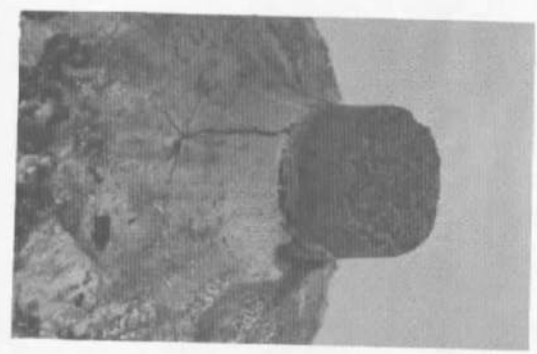
f. Model 5Q-20



g. Model 1P-3



h. Model 5Q-11

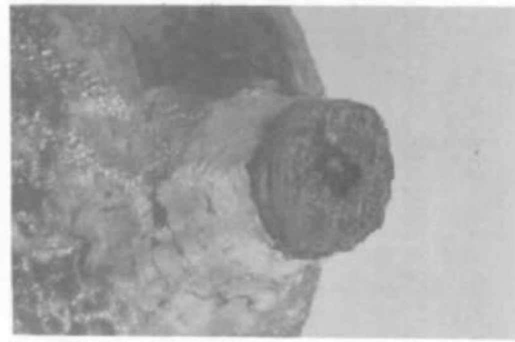


i. Model 2A

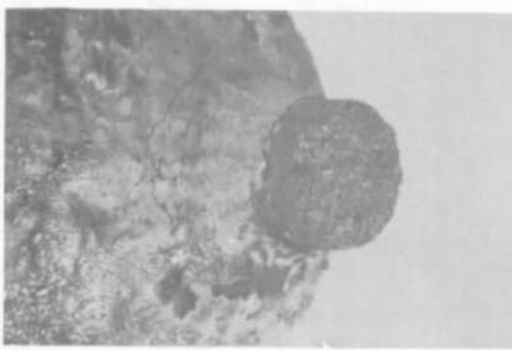
j. Model IPBN No. 1

Fig. 10 Continued

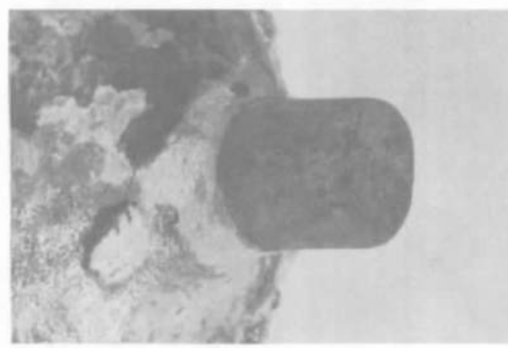
k. Model IPBN No. 2



l. Model CVD-4A



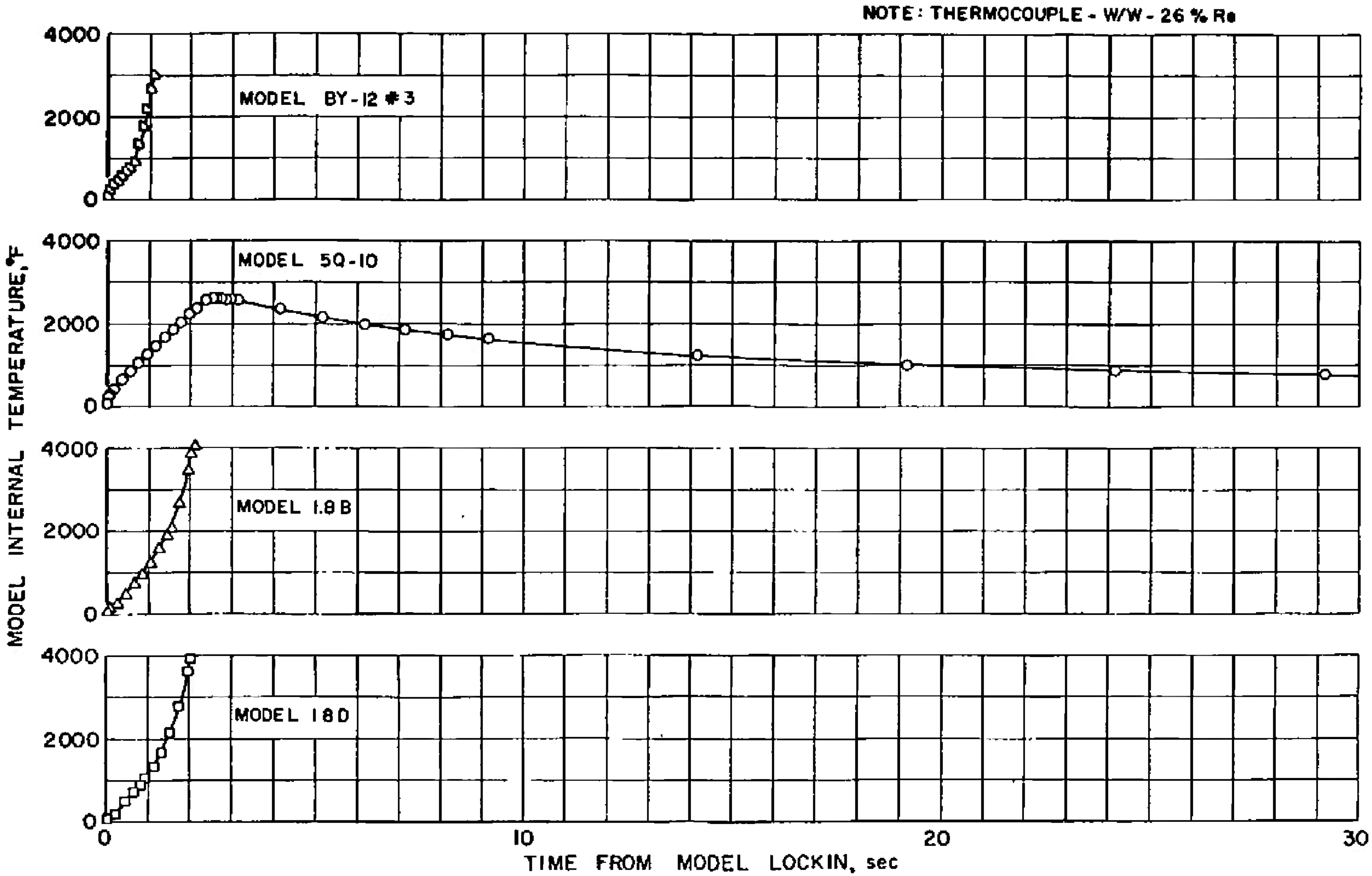
m. Model CVD-4C



n. Model IP-1A

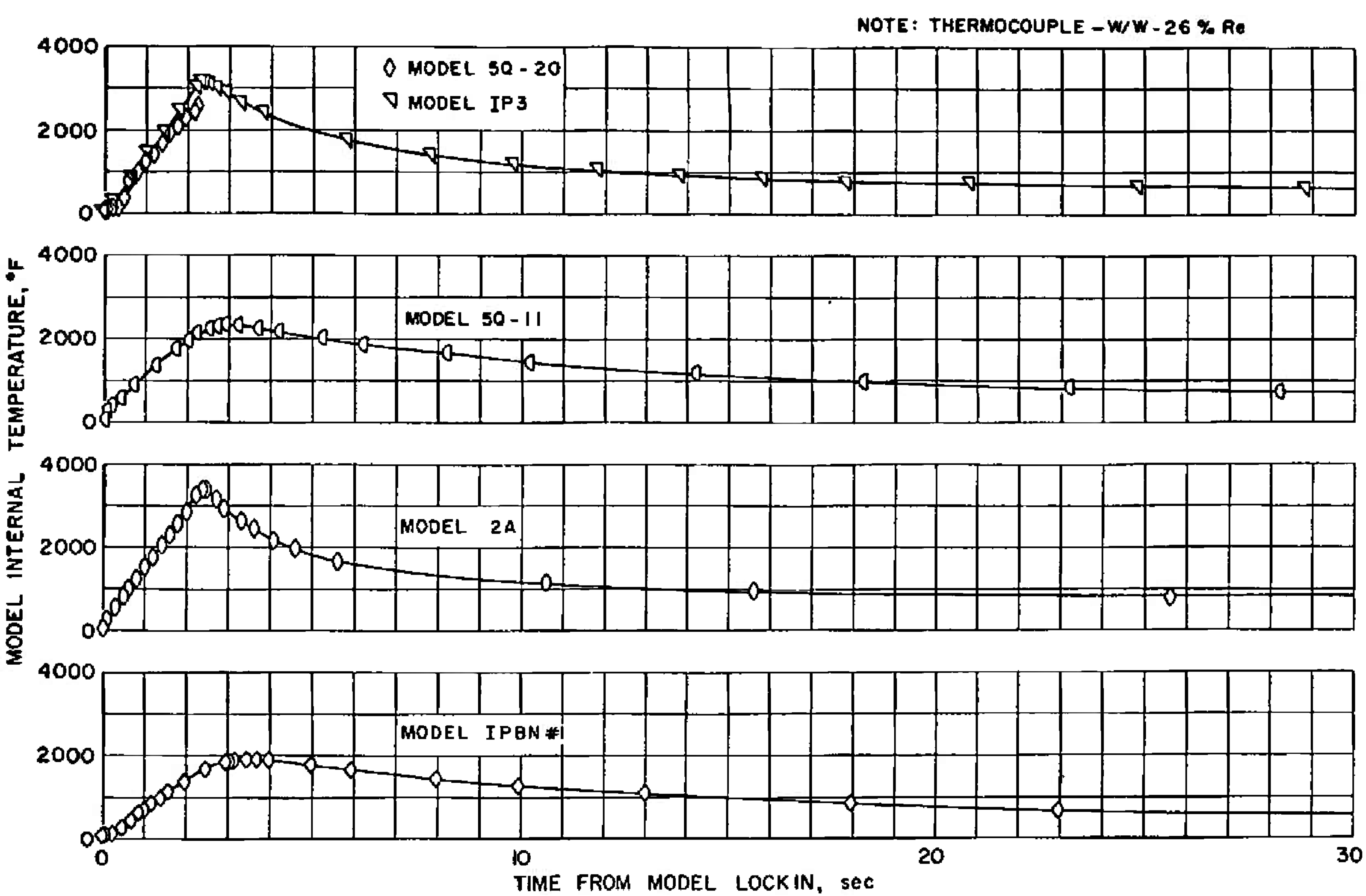
o. Model IP-9

Fig. 10 Concluded



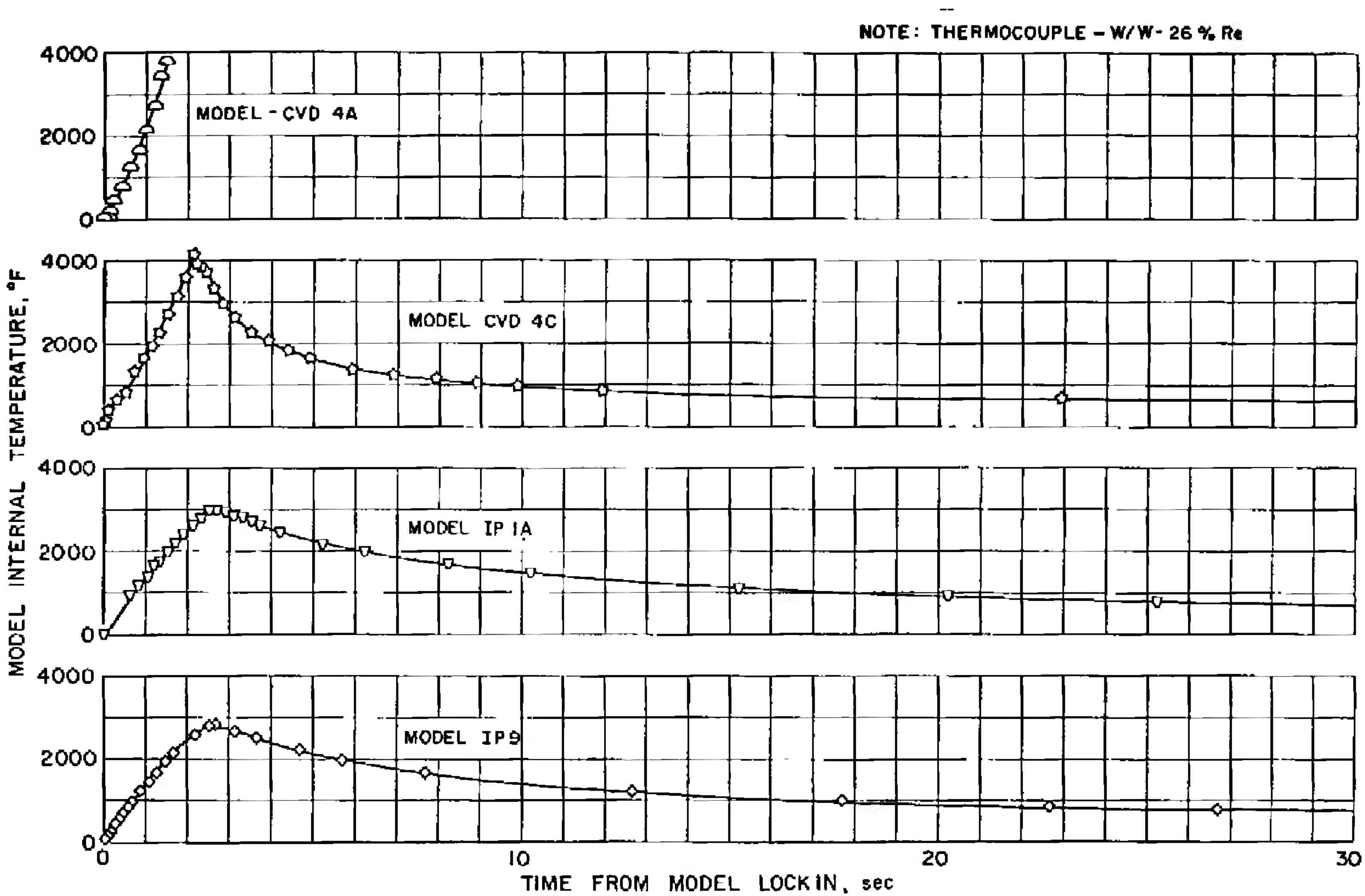
a. Run S-5

Fig. 11 Ablation Model Thermocouple Data



b. Run 5-6

Fig. 11 Continued



c. Run S-7

Fig. 11 Concluded

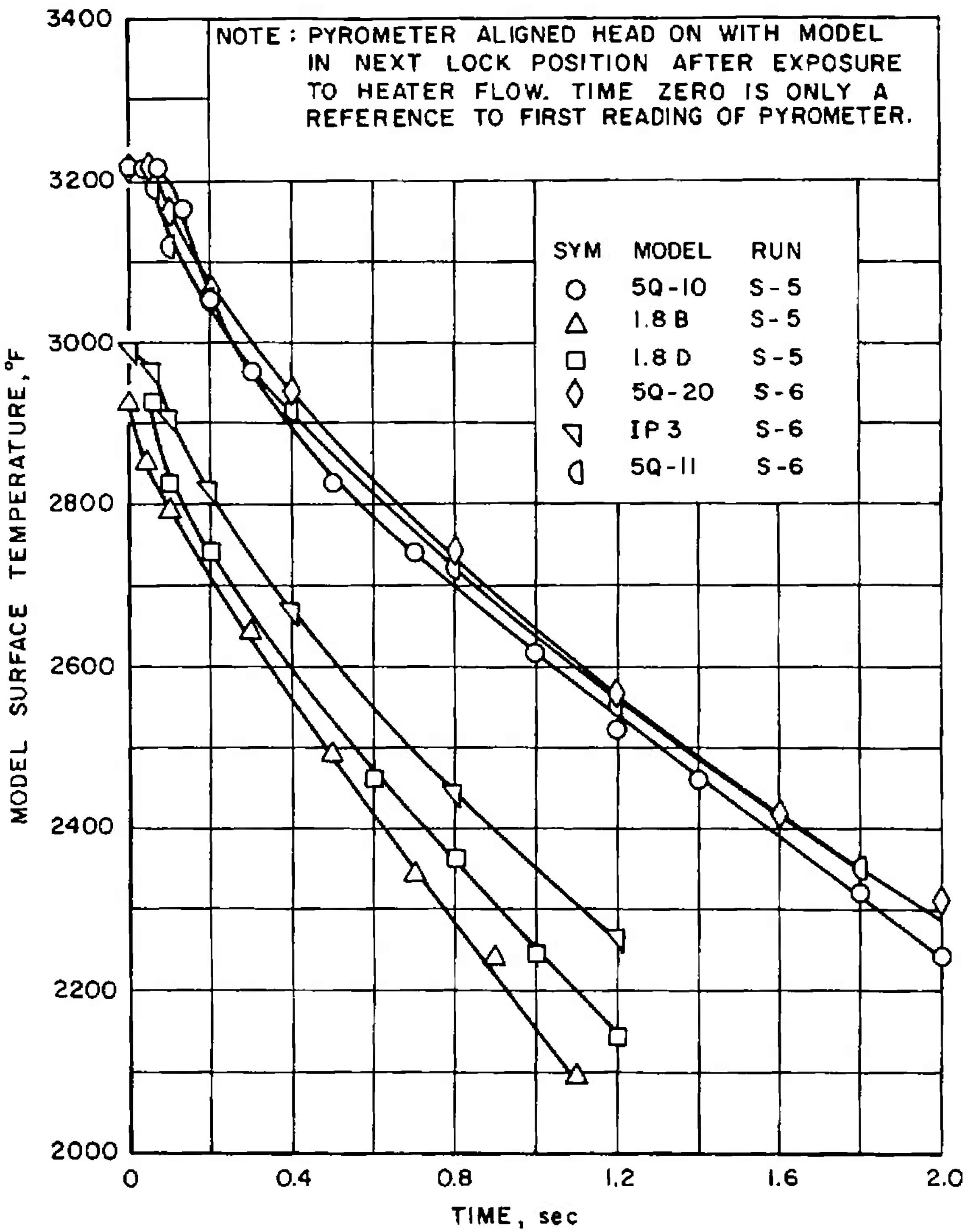


Fig. 12 Model Cooldown Pyrometer Data

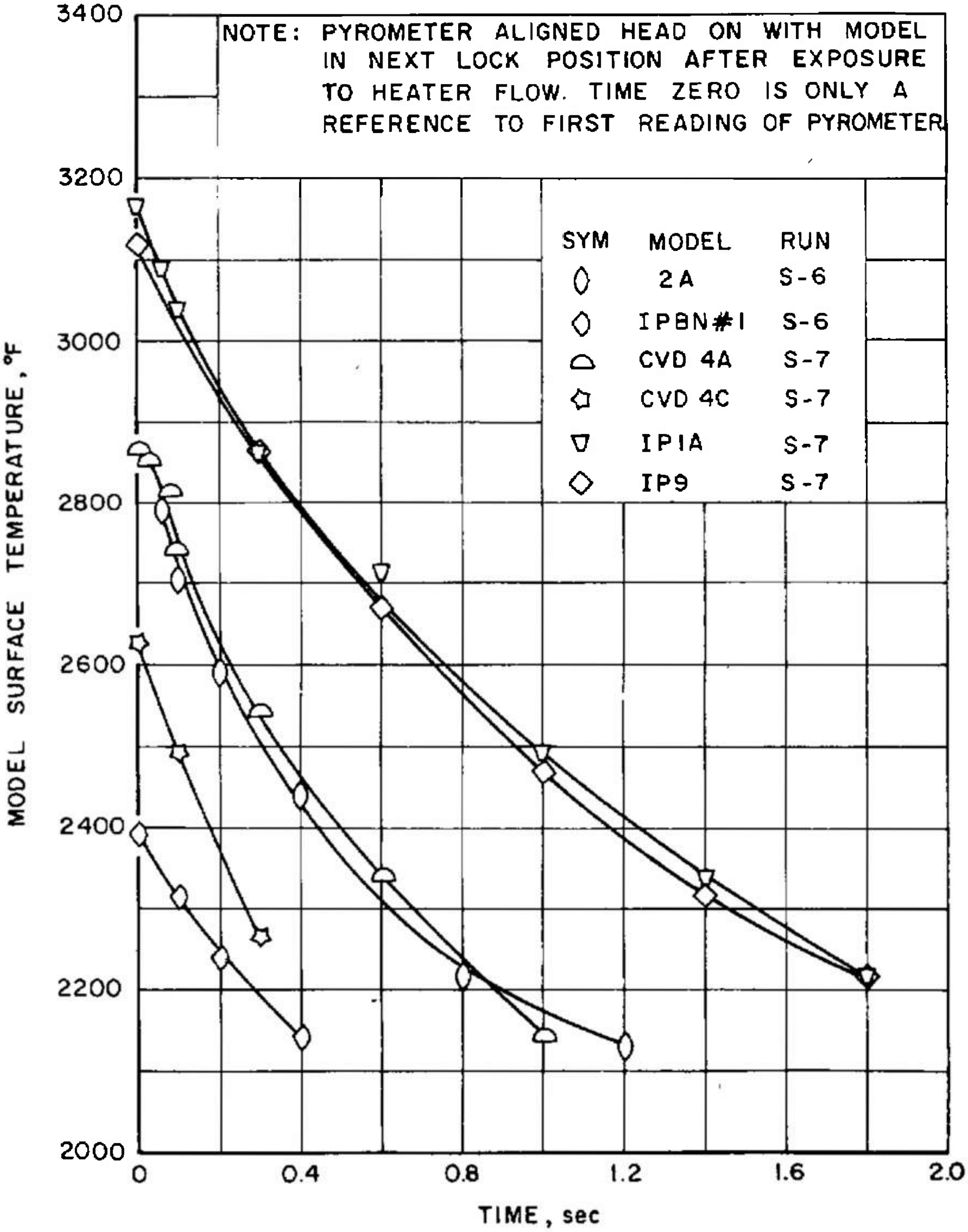


Fig. 12 Concluded

TABLE I
MOTION-PICTURE TEST LOG

Run Number	Camera Number	Camera Type	Film Type	Camera Speed, fps	Focal Length, in.	F/Stop	Filter	Shutter	Remarks
S-5	1	Hycam	7256	600	8	22	1.40/0 N.D.	10/1	
	2	D. B. Milliken	7256	400	6	22	0.3 N.D.	18 deg	Exposure Bright
	3	D. B. Milliken	7256	400	8	22	0.9 N.D.	7.5 deg	
S-6	1	Hycam	7256	600	8	22	1.40/0 N.D.	10/1	
	2	D. B. Milliken	7256	400	6	22	0.3 N.D.	18 deg	Exposure Bright
	3	D. B. Milliken	7256	400	8	22	0.9 N.D.	7.5 deg	
S-7	1	Hycam	7256	600	8	22	1.40/0 N.D.	10/1	
	2	D. B. Milliken	7256	400	6	22	0.3 N.D.	18 deg	Exposure Bright
	3	D. B. Milliken	7256	400	8	22	0.9 N.D.	7.5 deg	

TABLE II
MODEL PRE- AND POSTTEST WEIGHTS AND MEASUREMENTS

Run Number	Model Number	Preweights, gm	Prelength, in.	Postweights, gm	Postlength, in.
S-5	BY-12 No. 3	6.5091	1.608	3.5879	0.967
	PYC-F1-175	5.3488	1.604	***	0.5585
	5Q-10	6.9354	1.600	6.3033	1.4115
	1.8B	5.8624	1.609	4.4337	1.2080
	1.8D	5.9183	1.610	4.4597	1.1955
S-6	5Q-20	7.1620	1.620	6.5162	1.4455
	IP-3	5.7647	1.604	4.7591	1.3275
	5Q-11	6.8992	1.597	6.3122	1.4295
	2A	6.4213	1.611	5.0995	1.2780
	IPBN No. 1	4.0974	1.600	3.2445	1.2350
S-7	IPBN No. 2	4.1705	1.602	***	1.1075
	CVD-4A	5.9730	1.603	***	1.1200
	CVD-4C	5.8817	1.610	4.3287	1.1680
	IP-1A	5.7161	1.602	***	1.3835
	1P-9	5.9500	1.608	***	1.4205

***Posttest weight is not available because metal sleeve around sample could not be removed without sample damage.

TABLE III
MODEL TEST LOG

Run Number	Model Number	Model Configuration	Model Type	Sting Position	Exposure Time, sec	Number of Thermocouples	Thermocouple Type
S-5	BY-12 No. 3	Hemisphere	Ablation	1	2.21	1	W/W-26-percent Re
	PYC-F1-175	Hemisphere	Ablation	2	2.14	1	W/W-26-percent Re
	5Q-10	Hemisphere	Ablation	3	2.14	1	W/W-26-percent Re
	1.8B	Hemisphere	Ablation	4	2.13	1	W/W-26-percent Re
	1.8D	Hemisphere	Ablation	5	2.12	1	W/W-26-percent Re
S-6	5Q-20	Hemisphere	Ablation	1	2.16	1	W/W-26-percent Re
	IP-3	Hemisphere	Ablation	2	2.08	1	W/W-26-percent Re
	5Q-11	Hemisphere	Ablation	3	2.15	1	W/W-26-percent Re
	2A	Hemisphere	Ablation	4	2.14	1	W/W-26-percent Re
	IPBN No. 1	Hemisphere	Ablation	5	2.17	1	W/W-26-percent Re
S-7	IPBN No. 2	Hemisphere	Ablation	1	2.18	0	-
	CVD-4A	Hemisphere	Ablation	2	2.22	1	W/W-26-percent Re
	CVD-4C	Hemisphere	Ablation	3	2.14	1	W/W-26-percent Re
	IP-1A	Hemisphere	Ablation	4	2.16	1	W/W-26-percent Re
	IP-9	Hemisphere	Ablation	5	2.13	1	W/W-26-percent Re

TABLE IV
ARC HEATER TEST DATA

Run Number	Voltage, V	Current, I, amp	$\dot{m}$, lb/sec	p_t, atm	h_t, Btu/lb	η, percent	Estimated Model Stagnation Pressure, atm
S-5	8000	660	0.88	100	2390	41.5	53.5
S-6	8000	680	0.86	99	2530	42.7	53.0
S-7	8060	650	0.89	98	2310	41.0	52.5

TABLE V
SAMPLE MASS LOSS AND RECESSION RATE

Run Number	Model Number	Exposure Time, Δt_m, sec	Mass Change, Δm, gm	Length Change, ΔL, in.	Loss Rate, $\Delta m/\Delta t_m$, gm/sec	Recession Rate, $\Delta L/\Delta t_m$, in./sec
S-5	BY-12 No. 3	2.21	2.9212	0.641	1.322	0.290
↓	PYC-F1-175	2.14	*	1.045	*	0.489
↓	5Q-10	2.14	0.6321	0.188	0.295	0.088
↓	1.8B	2.13	1.4287	0.401	0.671	0.188
↓	1.8D	2.12	1.4586	0.414	0.688	0.195
S-6	5Q-20	2.16	0.6458	0.174	0.299	0.081
↓	IP-3	2.08	1.0056	0.276	0.483	0.133
↓	5Q-11	2.15	0.5870	0.168	0.273	0.079
↓	2A	2.14	1.3218	0.333	0.618	0.156
↓	IPBN No. 1	2.17	0.8529	0.365	0.393	0.168
S-7	IPBN No. 2	2.18	*	0.494	*	0.227
↓	CVD-4A	2.22	*	0.483	*	0.218
↓	CVD-4C	2.14	1.5530	0.442	0.726	0.206
↓	IP-1A	2.16	*	0.218	*	0.101
↓	IP-9	2.13	*	0.177	*	0.083

*Posttest weight is not available because metal sleeve around sample could not be removed without sample damage.

TABLE VI
MODEL PYROMETER DATA

Run Number	Model Number	Temperature Pyrometer No. 27*, °F	Remarks
S-5	BY-12 No. 3	4090	
↓	PYC-F1-175	-	Model failed during injection.
	5Q-10	4035	
	1.8B	4135	
	1.8D	4065	
S-6	5Q-20	4665	
↓	IP-3	4940	
	5Q-11	4615	
	2A	4815	
	IPBN No. 1	3965	
S-7	IPBN No. 2	4215	
↓	CVD-4A	5177	
	CVD-4C	5165	
	IP-1A	5052	
	IP-9	4965	

*Pyrometer No. 27 was filtered and focused on the model shoulder. Pyrometer readings are peak values measured while the model was exposed to heater flow.

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13. ABSTRACT

Three ablation test runs, involving 15 test models, were made in an arc-heated free-jet facility using air as the test fluid. Test runs were conducted to screen and examine the ablation performance of various materials with different microscopic structure. The investigation was accomplished at Mach number 2.3 with measured reservoir pressures ranging from 98 to 100 atm and enthalpies from 2310 to 2530 Btu/lb. Test models were hemisphere-cylinder specimens of composite materials. Most of the models were instrumented with a thermocouple embedded inside the specimen. The data measured during the present investigation are presented in a documentary manner with a minimum of analysis because the composition of the model material is proprietary. The models are referred to by number designation only.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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1 ablation tests						
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ablation performance						
microscopic structure						
supersonic flow						
2. Blunt nosed bodies - - ablation						